Shelter and Indoor Air

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Improvements in outdoor air quality that were achieved through the implementation of the Clean Air Act accentuate the quality of the indoor air as an important, if not dominant, factor in the determination of the total population exposure to air contaminants. A number of developments are adding important new determinants of indoor air quality. Energy conservation strategies require reductions in infiltration of outdoor air into buildings. New materials introduced in the construction and in the maintenance of buildings are contributing new air contaminants into the building atmosphere. Larger buildings require more and more complex ventilation systems that are less and less under the individual control of the occupants. All of these factors contribute to the current reality that indoor air contains more pollutants, and often at higher concentrations, than outdoor air. Especially in the larger buildings, it will be necessary to assure that an adequate quantity of fresh air of acceptable quality is provided to each individual space, and that no new sources of pollutants are added to a space or a whole building without appropriate adjustments in the supply of fresh air.

Introduction

There are complex interactions between indoor air quality, indoor climate, and other conditions of occupancy in residential buildings and nonindustrial workplaces that result in nonspecific complaints and concerns. Such complaints can sometimes be associated with the growth of microorganisms in a building and its systems. Health, the quality of life, and ultimately productivity of substantial segments of the population are affected in ways and to extents that are currently poorly described and quantified. Since a very large proportion of our daily lives is spent in various forms of shelter, an even larger proportion of our total exposure to a large number of air pollutants is determined by the building environment.

We actually spend, on average, 85 to 90% of our 24-hr day in some form of shelter, be it a home, a car, an office, school, or workplace. The shelter provides us with a microenvironment with an optimized temperature and protection from sun, wind, and precipitation. In the days of heavy outdoor air pollution our shelters also provided us with some protection from the peaks of that pollution. In the last few decades the outdoor air and the industrial workplace have attained much lower levels of air pollution as a result of the activities under the Clean Air Act and the Occupational Safety and Health Act.

In recent years the nonoccupational indoor environment is receiving an increased level of attention, and in some form or another, this is likely to continue and increase well into the twenty-first century. Future developments in this area are likely to be shaped by trends that are already discernable:

- Energy will be progressively more costly, and less flexible.
- Shelters will be larger buildings with higher densities of occupants because of energy considerations, limitations in available land, and in transportation systems.
- The materials surrounding us in our shelters will be more and more of manufactured synthetic rather than natural origin.
- The fraction of the population spending a large part of their 24-hr day in large, mechanically ventilated buildings will continue to increase; the total annual population exposure to complex building environments will therefore also increase.
- The current tendency towards diminishing individual control of personal environments in large buildings will continue.

Twenty years ago the quality of indoor air in the residential and the nonindustrial occupational environment was not seen as an important issue, and it was assumed to be adequate. Since then, a number of studies in the United States, West Germany, Italy, and the Netherlands have collected data on pollutant levels in several thousand residences (1–4). A working group of the World Health Organization reviewed these data (5) and concluded that in all these industrialized nations, the same large number of contaminants occurred in the residential environment in about the same concentrations and in the same distribution of concentrations. As might be expected, the concentrations are quite variable over space and time. For the majority of the pollutants examined, the concentrations indoors were higher or much higher than the outdoor concentrations, indicating that they were due to sources within the shelter.

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Table 1. Annual and lifetime intake of air, benzene, and toluene, based on median concentrations indoors and outdoors.

| | Lifetime intake of air | | Annual grams inhaled (3 hr out, 21 hr indoors) | | | |
| | | | Benzene median | | Toluene median | |
Age, years	RMV, L/min[a]	Annual m³	Indoors 10 µg/m³	Outdoors 3 µg/m³	Indoors 65 µg/m³	Outdoors 5 µg/m³
1	5	2628	0.023	0.001	0.149	0.002
10	10	5256	0.046	0.002	0.299	0.003
20	8	4205	0.037	0.002	0.239	0.003
70	7	3679	0.032	0.001	0.209	0.002
Lifetime total		307476	2.690	0.115	17.488	0.192

[a] RMV, *respiratory minute volume.*

These insights have important consequences for public health and for strategies for reduction in total population exposures to a whole range of air pollutants. Table 1 presents the annual air intake via the respiratory route and the annual and lifetime intake of benzene and toluene from the indoor and outdoor environment. The benzene and toluene concentrations in Table 1 are taken *from the median values reported in (5).*

It is clear that the dominant intake is from the indoor environment, and that also makes the indoor environment the most effective target for attempts to reduce the total population exposure. Another way in which we can evaluate the distribution of such indoor exposures is presented in Table 2. This table presents the output from a spreadsheet that can be used to assess the consequences that can be expected from the distribution of benzene exposure over the population, given the carcinogenic potency estimates for benzene.

Table 2 presents a comprehensive assessment of the health consequences of the distribution of benzene exposures, which was established in the Total Exposure Assessment Methodology (TEAM) study (1), relating it to the carcinogenic potency estimate developed by the Carcinogen Assessment Group (CAG) of the U.S. Environmental Protection Agency (EPA) and to the threshold limit value (TLV) for benzene. In addition, Table 2 places these outcomes into the total perspective of the total leukemia incidence in the United States. The footnote of this table contains the U.S. population, the TLV for benzene, and the unit risk per year per million people of leukemia per microgram per m³ of benzene in inhaled air. In addition, the background incidence rate and the annual U.S. mortality attributed to leukemia is given. The aggregate of the TEAM observations on benzene is given in the first six columns of Table 2. The last two columns provide the calculated attributable incidence of leukemia resulting from the exposures described in the first six columns, based on the population and unit risk numbers in the header. The form in which the existing exposure data and risk projections are given in Table 2 allows for the evaluation of the effectiveness of different exposure reduction strategies.

A similar projection can be made for the distribution of the risks of lung cancer attributable to indoor radon daughter concentrations as described in the U.S. (6). Table 3 presents such a spreadsheet for radon daughters. Exposures to benzene and radon would not generally lead to acute effects, nor would these exposures lead to recognition of an odor, except perhaps at the highest concentration in Table 2.

There have been occasions in which formaldehyde was introduced into residential environments from inappropriately formulated or installed urea formaldehyde foam insulation or from inappropriately fabricated chipboard. The rate of complaints involving formaldehyde in residential environments is now at a very much lower level than was experienced at the time of initial introduction of these products.

Occupants in a large number of buildings in the U.S. and in other industrialized nations have complained about acute adverse effects associated with their presence in the buildings. These conditions have been re-

Table 2. Exposures to benzene: assessment of health impact of total population exposure.[a]

| Population % | | Exposures, µg/m³ | | | | Excess mortality | |
Cumulative	Fraction	Night	Day	Outdoor	Breath	Outdoor	Total
10	10	0.80	1.5	0.3	0.5	0	1
25	15	4.70	5.5	1.2	3.5	0	10
50	25	13.00	13.0	4.9	9.0	3	41
75	25	25.00	25.0	11.0	18.0	7	78
90	15	42.00	51.0	16.0	33.0	6	87
95	5	61.00	75.0	21.0	48.0	3	42
99	4	210.00	120.0	32.0	80.0	3	82
100	1	350.00	160.0	40.0	105.0	1	32
Median exposure:		4.33	TLV/10000				
Total						23	374

[a]Total population base: 245.0 million; TLV (threshold limit value): 30 mg/m³; leukemia risk: 0.05/million people/year/µg/m³ exposure; annual background rate: 6.0/100,000 for a total of 14,700. According to this estimate this exposure causes 3% of total incidence.

Table 3. Exposures to radon daughters with median = 0.80 pCi/L: assessment of health impact of total population exposure.[a]

Population, %		Exposures		Lifetime risk per million	Excess lung cancer, total
Cumulative	Fraction	pCi/L	Bg/m³		
10	10	0.2	2.9	202	56
25	15	0.2	6.2	433	182
50	25	0.6	11.2	786	550
75	25	1.1	20.2	1411	988
90	15	2.2	39.2	2742	1152
95	5	3.9	70.3	4919	689
99	4	23.9	430.6	30139	3376
100	1	61.6	1108.6	77616	2173

Median exposure: 3.7% of TLV
Total   9166

[a]Total population base: 245.0 million; TLV (threshold limit value): 435.00 Bg/m3 EER; risk: lung cancer, 1.0/million people/year/Bg/m3 exposure; annual background rate: 55.0/100,000 for a total of 134,750; threshold level; 0 Bg/m³ EER. This exposure would account for 7% of total incidence.

ferred to as the sick building syndrome, or the tight or stuffy building syndrome. They have been reported in daycare centers of kindergarten schools in Sweden (7), in large apartment buildings in Denmark, and in office buildings in the United Kingdom and the United States. In all cases the occupant complaints have a great deal of similarity that has l to the characterization as a syndrome. The symptoms that are characteristically reported in excessive frequency are as follows: irritation of eyes, nose, and throat; headaches and dizziness; odors; fatigue and lethargy; wheezing and sinus congestion; skin rash and irritation; and nausea.

All these symptoms are reported with a 10 to 20% background incidence in any population, and it is not a simple matter to determine what the minimum incidence in a population should be and whether or not any reported incidence among the occupants in a given building at any time is significantly different from that minimum achievable incidence.

It is clear that an excess incidence of the symptoms previously discussed will have an effect on the productivity of an office population, but at the present time there are not any quantitative measures of such an effect. The effects are usually acute and reversible after leaving the offending building environment, and the complaints are usually limited to a minority of occupants.

When buildings that have given rise to occupant complaints are investigated along the lines of an occupational hazard evaluation, it is unusual to find a particular pollutant that is present in sufficient concentration to account for the occupant complaints. In a large number of such investigations the National Institute for Occupational Safety and Health (NIOSH) investigators found that inadequate ventilation was the most common cause identified (8). The most logical conclusion would then be that the inadequacy of the ventilation causes a number of contaminants to rise in concentration at the same time, and that it is the total concentration of the contaminants that is responsible for the occupant complaints, rather than the presence of any single contaminant in a critical concentration. Molhave (9) in Denmark has carried out experimental exposures of human volunteers to complex mixtures of organic air pollutants in which he reported

responses at concentrations which for each of the constituents would be below the threshold for perception. Little is known about the sensitization of some individuals at such low concentrations to render them more sensitive than the remainder of the population.

Ventilation systems and their components are often capable of supporting substantial growth of microorganisms such as fungi, algae, and bacteria. Such growth can occur in cooling towers, in the ventilation system itself in spray humidification systems, and in cooling coils. Microorganisms can be distributed via the ventilation air stream from the system to the occupied spaces, where sensitive occupants can be severely affected in reactions ranging from irritation to Legionellosis and Pontiac fever.

The systems supporting large buildings have become quite complex. A typical large office building might have 43 floors, each with 20,000 ft² of floor space. The ventilation air for the lower 20 floors is supplied by a machine floor near the 21st floor, and the remaining floors are served by another floor of blowers near the top floor. That means that air is distributed from a central location to each of 20,000 ft² on each of 20 floors. The air travels a long way through stacks and ducts both to and from a particular office. Even if the distribution was once perfect, it soon is disturbed by incompetent adjustment or by changes in the use of space or in the occupant density. Attempts to correct a local problem often create problems in other locations because of the interaction between these adjustments. If ductwork or equipment is inappropriately designed, installed, or maintained, it can support growth of microorganisms that get distributed throughout the building. Occupants can become sensitized to such microorganisms or to products from such growth. Some of the organisms are directly pathogenic such as Legionella. It is rare that all the equipment and ducts in a large building are kept clean with any consistency, and often they are not even accessible for maintenance and cleaning.

The foregoing discussion indicates that the ventilation air supply in a large building with a tight envelope is of critical importance. The quality of the air supplied can be degraded by microbiological growth in the system, by contamination of the intake air from vehicle exhausts, or

from the cooling tower drift. When the rate of supply to a space is inadequate, the contaminants released in the space are not diluted enough. Occupants have no direct control over either the quantity or the quality of ventilation air; as a result, they are likely to seek redress if the indoor air quality is felt to be less than adequate. In the twenty-first century we are likely to have to control the air quality in buildings as closely as the quality of the drinking water that is being supplied to the occupants. The supply of ventilation air in large buildings is likely to take on the characteristics of a regulated activity such as the potable water supply or the supply of safe and healthful food. It is also likely that there will be increased scrutiny of building materials, furnishings, maintenance, and cleaning products introduced into building spaces. It is not possible to design and operate ventilation systems in buildings that can deal effectively with the sudden and very large sources of contaminants that are regularly introduced whenever pesticides must be used or when wall or floor coverings are glued to the structure.

All of the foregoing discussion applies to residential environments with equal relevance. There are major differences between nonindustrial workplaces and residences: in a residence the density of occupants is usually much lower than in office buildings, and occupants in residential environments have a substantial amount of individual control over their immediate environment. In a residence the occupants determine whether and when pollutants are intoduced, and they can open windows.

The current revision of the American Society of Heating, Refrigerating and Air-Conditioning Engineers Ventilation Standard 82-1989(10) is attempting to deal as effectively as possible with current and future needs of architects, engineers, contractors, and owners and operators of buildings, but the state of our knowledge is quite inadequate to do much more than specifying empirically derived rates at which outdoor air must be supplied to interior spaces. Knowledge about the effects of indoor air pollutants on building occupants is quite inadequate to specify safe and acceptable levels in indoor spaces.

Regulations are perhaps not an effective approach to achieve improvements in indoor air quality, but interest by labor unions and the rapidly growing interest in the legal profession in tort actions on behalf of building occupants are likely to focus increasing attention on the problem of indoor air quality in public access buildings. At the present time we cannot estimate the economic leverage of indoor air quality in office buildings, but it does not require a complex calculation to show that even a very small effect on the productivity of office workers would justify a substantial research effort in the area of indoor air quality and also a substantial increase in cost of operation and maintenance of ventilation systems.

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